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Environmental Impact of Earthquake-Resistant Design: A Sustainable Approach to Structural Response in High-Seismic-Risk Regions

Alvaro Bohorquez [1], Esteban Viteri [1], Edgar Rivera [2] and Carlos Avila [2,*]

[1] Escuela Politécnica Nacional, Facultad de Ingeniería Civil y Ambiental, Quito 170143, Ecuador; alvaro.bohorquez@epn.edu.ec (A.B.); esteban.viteri@epn.edu.ec (E.V.)
[2] Universidad UTE, Facultad de Ciencias, Ingeniería y Construcción, Grupo de Investigación de Energía, Minas y Agua (GIEMA), Quito 170527, Ecuador. edgar.rivera@ute.edu.ec
* Correspondence: carlos.avila@ute.edu.ec; Tel.: +593999261838.

Abstract: This paper assesses the environmental impact of earthquake-resistant structural design decisions in high-risk seismic regions. As awareness of climate change increases, it becomes essential to critically assess the environmental impacts of design choices to advance sustainability in the built environment. Using a life cycle assessment approach, the study evaluates the environmental impact of earthquake-resistant structural design and construction in a building located in a high-risk seismic region (Quito, Ecuador). The assessment considers materials fabrication, transportation, and construction, and quantifies emission and consumption factors in a 'cradle to gate' approach. The study proposes three structural designs: Optimised Framed System (OFS), Optimised Dual System (ODS), and Equivalent Framed System (EFS) to identify the system with the highest structural performance and lowest environmental impact. The ODS demonstrated the optimal structural response, showcasing equal storey drift compared to the EFS, while emitting 38% less pollution. Furthermore, it only induced approximately 5% more pollution than the system with the lowest contamination levels (OFS). This study concludes that earthquake-resistant design has a direct impact on CO_2 emissions in the environment. An effective earthquake-resistant response could have lower levels of pollution; therefore, a balance could be achieved between a good structural response with a reduced environmental impact.

Keywords: earthquake-resistant design; environmental impact; life cycle assessment; sustainable buildings; storey drift

Introduction

The emission of greenhouse gases is annually increasing due to the non-controlled and unsustainable economic growth and industrialisation, leading to a global crisis and directly influencing climate change [1]. Greenhouse gases are produced in all the sectors including energy (73.2%), agriculture, forestry, and land use (18.4%), waste (3.2%) and industry (5.2%); being energy consumption in buildings, the second most pollutant factor in the whole energy sector [2,3]. Globally, the construction industry contributes approximately 40% of the annual carbon emissions [4]. Moreover, in terms of energy consumption and environmental impact, the construction sector annually consumes more than 35% of energy resources and requires approximately 50% of natural resources [4,5]. Therefore, the sustainability of the construction field may be considered poor.

Considering the severe environmental issues entailed in the construction sector, particularly in multiple stores buildings, studies [1,6–8] were conducted to identify the incidence of buildings in the generation of greenhouse pollutants. Although these investigations provided valuable data on the building's carbon footprint, most of these studies primarily focused on the selection of the materials but not on the consumption rates of either CO_2 emissions or energy. For instance, the CO_2 emissions of reinforced concrete were lower than the emissions in structural steel buildings [1]. Contrasting results were found in a study that evaluated both energy consumption and CO_2 emissions in concrete,

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steel, and wood buildings [8]. In this case, lower emissions were registered in the steel-based structure which could be explained by the analysed stages in the life-cycle assessment.

There are limited data concerning the incidence of construction components, such as the lateral loading system and the number of floors, in the carbon footprint of an edification building [1,8,9] . Measurement of the CO_2 emissions produced in the construction process of a roof structure highlighted that voided slabs were less pollutant than ordinary slabs [10]. Another investigation [9] demonstrated that steel had the highest environmental impact in the construction and demolition of a multi-store building (life cycle assessment). This study considered other construction variables besides the main building materials including the number of floors and structural system. In a study conducted in Mexico, it was found that buildings which used solid concrete for ceilings and walls, and aluminium frame windows left a larger carbon footprint than structures that use ceramic-based walls, vault ceilings and PVC-based windows [11]. Another interesting observation in Peru [12] although not surprising, showed that most of the CO_2 emissions were produced during the construction stage rather than in the transportation stage.

In Ecuador, and in general in developing countries, there is limited information concerning the carbon footprint of buildings and how sustainable they are. A first investigation in Ecuador, into the energy consumption and CO_2 emissions in the fabrication of ready-mix concrete was proposed by Vázquez [13]. Another evaluation of a building in Ecuador was accomplished by Narvaez and Maldonado [14] who found out that the architectural design influences levels of CO_2 emissions in an edification.

Designing buildings in Ecuador and in other seismic countries is challenging [15]. The design of buildings considers seismic design theory to evaluate lateral loads, materials, and structure altitude (number of floors). In addition to the structural characteristics of the building, other factors such as building performance, and direct and indirect costs are normally considered, but, the environmental impact is usually disregarded. Therefore, there is limited data available, particularly in developing countries located in seismic areas, that quantifies the relation between seismic resistance and sustainability. With this in mind, the aim of this study is to analyse the impact of the lateral structural design in the environment by conducting a life-cycle assessment (LCA) in the manufacturing, transportation and construction phases.

Materials and Methods

2.1. Case Study Building

The case study building was stablished in the district with the most mid-altitude buildings in Quito (Table 1) [16]. The dimensions of the building were chosen after conducting a statistical analysis with an 80% confidence level of the types of buildings in the area (Table 1). Additionally, it is important to note that the building's foundation is on a type D soil [17,18].

Table 1: Dimensions and location of the case building study

Parameter	Unit	Magnitude
Latitude	°	-0.178332
Longitude	°	-78.436299
Number of floors	u	7
Number of basements	u	3
Height without basements	m	18.55
Total height (including basements)	m	26.50
Floor area	m^2	255.43
Total floor area	m^2	4150.1
Bearing capacity	tonnes/m^2	18.34

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2.2 Structural Design Alternatives

The case study building consisted of three structural systems, i.e. Optimised Frame System (OFS) (Figure 1a), Optimised Dual System (ODS) (Figure 1b) and Equivalent Frame System (EFS) (Figure 1c). An optimised system considers the Ecuadorean National Standards [19] to define the minimum cross-sectional area of the structural elements to provide an adequate mechanical response to specific structural demands. However, the OFS presents a drift of 1.75%, which is at the limit of what is permissible according to the Ecuadorian construction norm, set at 2%. This is important because high drifts near this limit contribute to the failures of non-structural elements such as masonry. These detrimental outcomes in a building were observed in a recent earthquake in Pedernales – Ecuador in 2016 where masonry debris involved deaths [20].

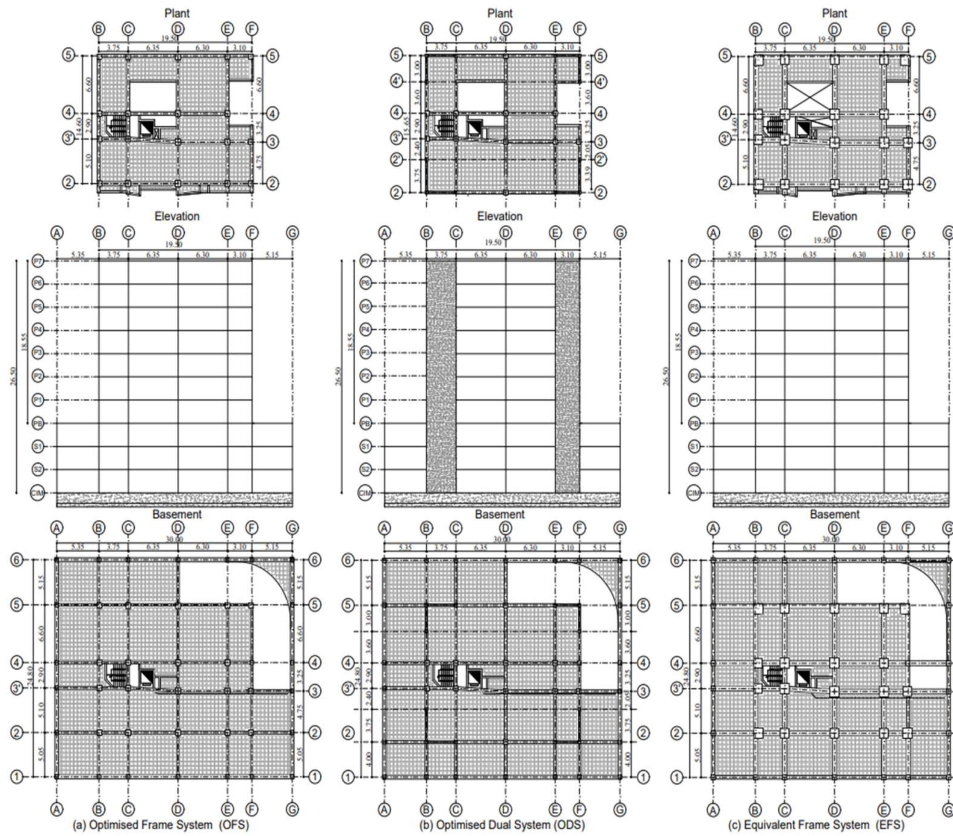

Figure 1. Structural configuration of the three systems (a) OFS, (b) ODS and (c) EFS.

The OFS constitutes a more flexible structure; therefore, it has a greater floor drift compared to the ODS; in other words, these systems do not exhibit the same level of structural behavior against seismic actions, since the maximum floor drift of the OFS was 1.75%; while for the ODS, it was 0.83%. Given that the ODS is characterized by its structural rigidity, it is possible that it requires less material to achieve the same resistance and stability as the OFS, which relies on flexibility to absorb and dissipate seismic energy. This means that constructing the ODS could imply less extraction of natural resources and a lower generation of CO2. Additionally, the reduction in the amount of material used could also have a positive impact in terms of energy associated with the production and distribution of those materials.

Therefore, from an environmental perspective, it is argued that the ODS is more sustainable than the OFS due to its potential to minimize the use of construction materials and thus reduce its overall environmental footprint. Since these systems are different, they cannot be directly comparable to each other. For this reason, the research was extended to a third structural system known as the Equivalent

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Frame System (EFS). In this system, the same level of performance was achieved in terms of floor drift as the ODS (0.83%). Therefore, a structurally equivalent system to the OFS was attained to enable a comparison between them and observe the differences between CO_2 emissions and energy consumption.

The three systems considered continuum sections, symmetric columns and beams for the framed systems (OFS and EFS) and proportionality in the length of the structural walls of the dual system. The Ecuadorean National Standards [19] were considered in this study to compute the optimum dimensions of the structural components per each structural system. The dead load of the whole structural system was 0.45 tonnes/m^2 while the superimposed dead load of 0.22 tonnes/m^2, which corresponded to permanent load (e.g. mezzanines and subfloors) and 0.08 tonnes/m^2 for the roofs. Moreover, we considered the postulates of the NEC-15 [21] to include a live load of 0.20 tonnes/m^2. Finally, the Yield stress (fy) of the steel, compressive resistance (f'c) of the concrete and allowable compressive strength of soil were assumed as 240 MPa, 28 MPa, and 18.34 tonnes/m^2 respectively (Table 2).

Table 2. Detail of service loads and mechanical properties of materials.

Description	Magnitude	Units
Self-weight of slab	0.45	tonnes/m^2
Permanent mezzanine loads	0.22	tonnes/m^2
Permanent roof load	0.08	tonnes/m^2
Total dead load of mezzanine	0.67	tonnes/m^2
Total dead load of roof	0.53	tonnes/m^2
Live load	0.2	tonnes/m^2
Yield stress of reinforcing steel (fy)	420	MPa
Compressive strength of concrete (f'c)	28	MPa
Allowable compressive strength of soil	18.34	tonnes/m^2

Structural components such as stairs, vehicular ramp, retaining walls and roof slabs were the same in the three structural systems. The staircase consisted of roof slabs of thickness of 15 cm, tread of 25 cm and risers of 19 cm. The vehicular ramp had a slope of 12.5% constructed in a deck system with a thickness of 15 cm. The retaining walls varied in thickness across the three subsoils with 35 cm, 40 cm and 45 cm.

Roof slabs consisted of a two-way slab with a compressive layer of 5 cm, reinforced with structural joists of 10x20 cm and voided slabs made of merged concrete blocks of 40x40x20cm.

In general, a structure can be calculated using procedures for obtaining lateral forces, either static or dynamic. The dynamic response analysis, using the SRSS method for combining different dynamic responses, were based on the structural configuration, allowing the incorporation of torsional effects and vibration modes other than the fundamental. The seismic load was defined considering the seismic hazard of the structure's site based on the Ecuadorian standard [21]. The dynamic effects of seismic activity were modelled using a design response spectrum that considers a fraction of the structure's critical damping [21]. The seismic-resistant design of the three structural systems aims to prevent structural collapse during earthquakes, with the objective of safeguarding the lives of occupants. To achieve this design philosophy, all three systems were designed to have the capacity to resist seismic forces, maintain storey drifts below the allowable limit specified in Ecuadorean standards (2%) [21], and dissipate inelastic deformation energy (Table 3).

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Table 3. structural variables per system.

System	Material	Period		Vibration modes			Reactive weight [tonnes]	Base shear [tonnes]	Max storey drift in X [%]
		ETABS [s]	NEC-15 [s]	1st in X	2nd in Y	3rd in RZ			
OFS	RC	0.834	0.762	73%	77%	73%	2011	277	1.75
ODS	RC	0.538	0.492	66%	67%	67%	1902	314	0.83
EFS	RC	0.541	0.762	69%	73%	71%	3295	545	0.82
OFS – EFS (% Difference)	-	35%	35%	10%	13%	8%	3%	-	53%
ODS – EFS (% Difference)	-	1%	35%	4%	8%	7%	42%	-	1%

Note: X is displacement across the X-axis; Y is displacement across the Y-axis; RZ is rotation around the Z axis; Reactive weight is the total weight of the superstructure; Max drift in X is the largest drift corresponding to the X-axis; RC is reinforced concrete

1.3. Structural design

Reinforce concrete elements sections and Steel-reinforcement were quantified using the [22] and [19] and the Load and Resistance Factor Design (LRFD) approach as it correlates the mechanical resistance of each component with the necessary resistance according to load combinations (Equation 1). The equation shows that Rn is the nominal resistance, ϕ is the resistance factor, $\phi.R_n$ is the resistance design and $\sum(\lambda_i.Q_i)$ is the most unfavourable stress (Table 4).

$$\sum(\lambda_i.Q_i) \leq \phi.R_n \quad (1)$$

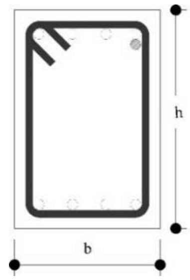
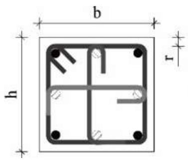
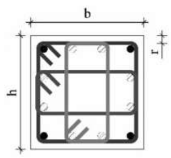
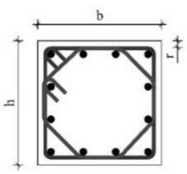
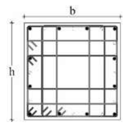
It is worth clarifying that the three structural systems share a similar design in the foundation beams due to the presence of multiple basement levels, as these contribute to reducing seismic moments on the foundation due to the lateral confinement provided by the soil.

2.4 Life Cycle Assessment of the Structural Systems

The life cycle assessment entails the evaluation of all the carbon emissions during the different phases to construct a building. In this study, we conduct a life cycle assessment in the three structural systems described above, which are the OFS, ODS and EFS, to identify the system with the lowest carbon emission and energy consumption.

The most important environmental variable to evaluate the impact of human activities in nature is the emission of greenhouse gases (i,e. CO_2 emissions) into the atmosphere. CO2 emissions in the construction industry are not only limited to the construction phase of the building but also to the manufacturing, production, transportation, and distribution processes of the construction materials. These stages were followed to agree with the PAS 2050:2011 [23] standard. A detailed view of the processes behind constructing a building is described in the process workflow (Figure 2).

Table 4. Final cross sections of structural systems.

	**OFS**			
	Type of beam	**b [cm]**	**h [cm]**	**r [cm]**
	V1 (P1-P7)	40	60	4
	V2 (S2-PB)	30	50	4
	V3 (S2-P7)	25	25	4
	ODS			
	V1 (P5-P7)	30	50	4
	V2 (S2-P4)	35	55	4
	V3 (S2-P7)	25	25	4
	EFS			
	V1 (S2-P7)	55	85	4
	V2 (S2-P7)	25	40	4
	**OFS**			
	Type of column	**b [cm]**	**h [cm]**	**r [cm]**
	C1 (P5-P7)	50	50	4
	C2 (P5-P7)	55	55	4
	C3 (P5-P7)	50	55	4
	C4 (P5-P7)	55	60	4
	ODS			
	C1 (P5-P7)	50	50	4
	**OFS**			
	C1 (PB-P5)	60	60	4
	C2 (PB-P5)	65	65	4
	C3 (PB-P5)	60	65	4
	C4 (PB-P5)	65	70	4
	ODS			
	C1 (PB-P5)	55	55	4
	**OFS**			
	C1 (S3-PB)	60	60	4
	C2 (S3-PB)	65	65	4
	C3 (S3-PB)	60	65	4
	C4 (S3-PB)	65	70	4
	C5 (S3-PB)	45	45	3
	ODS			
	C1 (SB3-PB)	55	55	4
	**EFS**			
	Type of column	**b [cm]**	**h [cm]**	**r [cm]**
	C1 (P5-P7)	110	110	4
	C2 (P5-P7)	100	100	4
	C1 (S3-P5)	120	120	4
	C2 (P5-P7)	100	100	4

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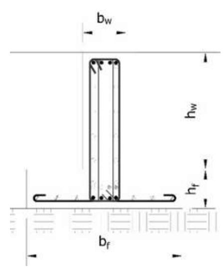
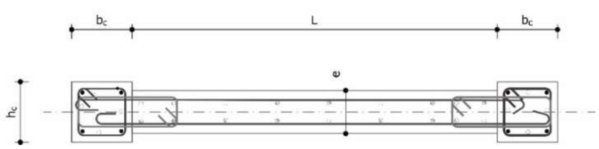
OFS				
Type of foundation beam	**bf [cm]**	**hf [cm]**	**bw [cm]**	**hw [cm]**
Inverted T Edge Beam	300	40	45	120
Inside Inverted T Beam	160	40	45	120
ODS				
Type of foundation beam	**bf [cm]**	**hf [cm]**	**bw [cm]**	**hw [cm]**
Inverted T Edge Beam	300	40	45	140
Inside Inverted T Beam	160	40	45	140
EFS				
Type of foundation beam	**bf [cm]**	**hf [cm]**	**bw [cm]**	**hw [cm]**
Inverted T Edge Beam	300	40	45	140
Inside Inverted T Beam	170	40	45	140



ODS				
Type of wall	**bc [cm]**	**hc [cm]**	**L [cm]**	**e [cm]**
M1- Lower	35	35	340	25
M1- Upper	30	30	345	20
M2- Lower	35	35	265	25
M2- Upper	30	30	270	20
M3- Lower	35	35	275	25
M3- Upper	30	30	280	20



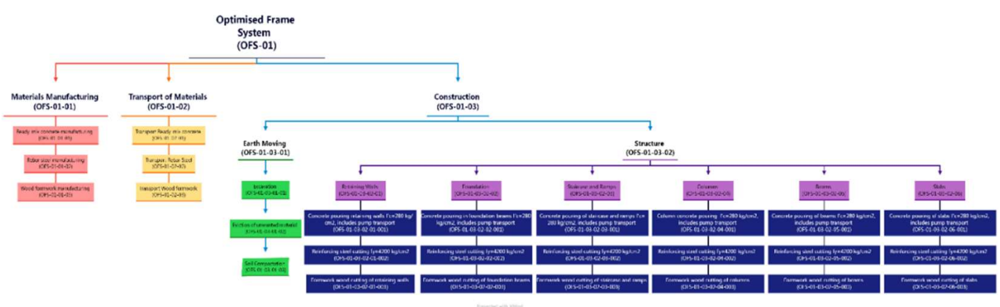


Figure 2. Work Breakdown Structure of the Optimised Frame System.

2.4.1. Materials Quantification

Each of the three structural systems, comprising beams, columns, stairs, and other elements, has a direct impact on the total carbon emissions during the building's design, material provision and construction. In this study, the components of each structural system, such as walls, stairs, and slabs, were fabricated with materials such as concrete, rebar steel, and wood (Table 5). In addition to the

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concrete elements, other sources of carbon emissions include excavation, soil disposal, and activities related to backfill material in foundations (Table 6).

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Table 5. Material Quantities for Key Structural Elements.

Structural Element	OFS			ODS			EFS		
	Concrete [m³]	Rebar Steel [tonnes]	Wood Formwork [tonnes]	Concrete [m³]	Rebar Steel [tonnes]	Wood Formwork [tonnes]	Concrete [m³]	Rebar Steel [tonnes]	Wood Formwork [tonnes]
Retaining Walls	317.11	9.72	2.38	317.11	9.77	2.38	317.11	9.72	2.38
Foundation Beam	441.36	31.11	1.54	473.47	50.92	1.68	482.09	47.78	1.66
Staircase and Ramps	62.86	12.07	0.57	62.86	12.07	0.57	62.86	12.07	0.57
Beams	319.97	40.57	2.67	257.24	19.42	2.33	639.17	73.67	3.68
Columns	214.22	47.74	2.28	120.61	31.68	1.43	704.54	155.28	4.08
Shear Wall	-	-	-	205.24	27.48	2.56	-	-	-
Slab	387.82	33.44	5.38	392.29	33.53	5.44	342.45	33.24	4.75
Total	**1743.34**	**174.65**	**14.83**	**1828.83**	**184.86**	**16.39**	**2548.21**	**331.77**	**17.13**

Table 6. Quantification of soil involved during the construction phase. Soil Activity.

Soil activity	**OFS**	**ODS**	**EFS**
Excavation Volume [m³]	7228.97	7228.97	7228.97
Unwanted material [m³]	6017.83	6017.83	6017.83
Filling material [m³]	769.78	737.67	729.05

2.4.2. Emission and energy consumption factors per material

The CO_2 emission factors (in tonnes of CO_2 per material unit) and energy consumption factors (in MJ per material unit) quantify the pollutants released during the fabrication of building materials, such as ready-mixed concrete or wooden formwork, and their impact on the environment. The assessment of these factors considered all stages involved in the fabrication of a building material, including the extraction of raw materials from the quarry and their transportation [24]. The EF and CF data for the calculation of gas emission and consumption factors were obtained from various sources (Table 7) [25–27].

Table 7. Emission and energy consumption factors in materials.

Material	EF [tonnes of CO_2 eq./u]	Source	Commentary	ECF [MJ/u]	Source
Concrete [m³]	0.252	[26]	University of Bath Carbon and Energy Inventory. f'c= 28 MPa	3623.190	[26]
Rebar Steel [tonnes]	1.99	[26]	University of Bath Carbon and Energy Inventory	19000.000	[27]
Wood Formwork [tonnes]	0.613	[25]	Study carried out at the University of La Coruña in MDP boards	3297.160	[25]

2.4.3 Emission and consumption Factors in Machinery and Equipment

The construction industry relies heavily on machinery and instruments for various processes involved in building construction, such as materials transportation, soil compaction, and excavation. Most of the machinery used in construction runs on fossil fuels and electricity, which makes them significant sources of CO_2 emissions. The fuel efficiency of machinery was measured in litres of fuel per hour (Table 8) [9,28].

Table 8. Fuel efficiency in machinery and equipment.

Equipment and machinery	Efficiency [L/u]	Source
Dump Truck 6x4, 10m³; 280hp, [km]	0.765	[28]
Cargo Truck 5 tonnes [km]	0.60	[28]
Concrete Mixer Truck; 3 axis; 8 m³; 300 hp [km]	0.77	[28]
Concrete Mixer Truck; 3 axis; 300 hp [h]	5.21	[24]
Vibratory plate compactor 7 hp [h]	1.10	[24]
Concrete vibrator (1.5"); 4 hp [h]	1.03	[24]
Backhoe 0.2 m³; 62 hp [h]	5.21	[24]
Front Loader 1.5-1.7 and D3; 80 hp [h]	13.93	[24]
Concrete Pump BSA 1000 1005 D3B C 75 hp [h]	15.00	[24]

Sources of CO_2 emissions were classified based on their use in building construction, such as transportation of equipment (e.g., trucks), construction machinery (e.g., concrete mixer machine), and electric instruments (e.g., electric circular saw) [10,29] (Tables 8 and 9).

Table 9. Electrical equipment power.

Equipment	Potency	Source
Chainsaw [W]	1200.000	[29]

It is noteworthy that the contribution of CO_2 emissions from electric instruments is much lower than those produced by fossil fuels (approximately eight times lower than fossil fuels) [10]. The gas emission factor of diesel machinery (EF_{mach}) was calculated by multiplying the fuel efficiency of machinery (n_{mac}) (Tables 8 and 9) with the gas emission factor of diesel (EF_{diesel}) (Table 10) (Equation 2). The machinery consumption factor (FC_{mach}) was calculated by multiplying the fuel efficiency of machinery (Tables 8 and 9) with the diesel consumption factor (FC_{diesel}, refer to Table 10) (Equation 3). The resulting factors are presented in Table 11.

$$EF_{mach} = n_{mach}\left[\frac{L}{km}\right] * EF_{diesel}\left[\frac{tonnes\ of\ CO_{2_{eq}}}{L}\right] \tag{2}$$

$$CF_{mach} = n_{mach}\left[\frac{L}{km}\right] * CF_{diesel}\left[\frac{MJ}{L}\right] \tag{3}$$

Table 10. Emission and energy consumption factors due to the consumption of fuel (diesel) and electrical energy.

Energy Source	EF [tonnes of CO_2 eq./u]	ECF [MJ/u]	Source
Fuel (Diesel) [L]	0.0025	34.68	[30]
Electric Power [MWh]	0.451	3600	[31]

Table 11: Emission and energy consumption factors in equipment and machinery.

Equipment and machinery	EF[tonnes of CO_2 eq/u]	CF [MJ/u]
Dump Truck; 6x4 10m^3; 280hp; [km]	0.0019	26.54
Cargo Truck; 5 tonnes; [km]	0.0015	20.70
Concrete Mixer Truck; 3 axis; 8 m^3; 300 hp; [km]	0.0019	26.54
Concrete Mixer Truck; 3 axis; 300 hp; [h]	0.0131	180.68
Vibratory plate compactor 7 hp; [h]	0.0028	38.15
Concrete vibrator (1.5"); 4 hp; [h]	0.0026	35.72
Backhoe; 0.2 m^3; 62 hp; [h]	0.0131	180.68
Front Loader; 1.5-1.7 m^3; 80 hp; [h]	0.0351	483.09
Concrete Pump BSA 1000 1005 D3B C 75 hp; [h]	0.0378	520.20
Chainsaw; [h]	0.0005	4.32

2.4.4 Materials transportation

Material transportation (Table 12) involves the movement of construction materials from the distribution depot to the building site [9]. In this study, the transportation analysis was conducted for ready-mixed concrete, steel reinforcement bars, and wooden formwork. Additionally, the transportation of waste from the building site to the construction material ºwaste disposal site was also considered. The total distance travelled by the materials was computed by multiplying the number of trips (Equation 4) by the distance travelled.

$$Number\ of\ travels = \frac{Quantity\ of\ the\ required\ material\ (units)}{Loading\ capacity\ of\ the\ transportation\ medium\ (units)} \quad (4)$$

Table 12. Results of analysis of transport of materials in OFS.

Transportation	Type of Transport	u	Loading capacity	Required quantity	No. Trips [u]	Distance [km]	Total distance [km]
Concrete	Concrete Mixer Truck; 3 axis; 8 m^3; 300 hp [km]	m^3	8	1743.34	436	7.8	3400.8
Rebar Steel	Cargo Truck 5 tonnes [km]	tonnes	5	174.65	70	6.2	434
Wood formwork	Cargo Truck 5 tonnes [km]	tonnes	5	14.83	6	2.3	13.8
Unwanted material	Dump Truck 6x4m, 10m^3; 280hp [km]	m^3	10	6017.83	1204	12.5	15050

2.4.5 Assessment of CO_2 Emissions and Energy Consumption per Activity

CO2 emissions and energy consumption were evaluated from the fabrication of materials stage to the construction of the building (Figure 2). To evaluate the emission factor (EF) and consumption factor (CF) of each activity, we propose a new methodology that considers the inputs of the sources of pollution, such as machinery, materials, and transport to convert the units of the different polluting sources into a single activity work unit (Equations 5 and 6).

$$EF_{activity} = (EF_{machinery} + EF_{material} + EF_{transport})\left[\frac{tonnes\ of\ CO_{2_{eq}}}{u}\right] \quad (5)$$

$$CF_{activity} = (CF_{machinery} + CF_{material} + CF_{transport})\left[\frac{MJ}{u}\right] \quad (6)$$

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The calculation of total emissions and energy consumption is based on the multiplication of the FE and CF per activity by the total number of activities performed, respectively (Equations 7 and 8, Table 13).

$$FE_{activity} = EF_{activity}\left[\frac{tonnes\ of\ CO_{2_{eq}}}{u}\right] quantity_{\ activity}[u] \tag{7}$$

$$CF_{activity} = CF_{activity}\left[\frac{MJ}{u}\right] quantity_{activity}[u] \tag{8}$$

Table 13. Results of environmental evaluation in the OFS.

No.	Code	Activity	u	Quantity	EF	ECF	Total Emission	Total Energy Consumption
					[tonne of CO_2 eq./u]	[MJ/u]	[tonnes of CO_2 eq]	[MJ]
1	**OFS-01-01**	**Materials Manufacturing**						
2	OFS-01-01-01	Ready-mix concrete manufacturing	m³	1743.34	0.25	3623.19	439.322	6316455.86
3	OFS-01-01-02	Rebar steel manufacturing	tonnes	174.65	1.99	19000	347.557	3318383.44
4	OFS-01-01-03	Wood formwork manufacturing	tonnes	14.83	0.61	3297.16	9.091	48899.32
5	**OFS-01-02**	**Transport of Materials**						
6	OFS-01-02-01	Transport Ready-mix concrete	km	3400.8	0.0019	26.54	6.554	90272.39
7	OFS-01-02-02	Transport Rebar Steel	km	434	0.0015	20.7	0.652	8985.83
8	OFS-01-02-03	Transport Wood formwork	km	13.8	0.0015	20.7	0.021	285.72
9	OFS-01-03	Construction						
10	OFS-01-03-01	Earth Moving						
11	OFS-01-03-01-01	Excavation	m³	7228.97	0.0007	9.03	4.741	65307.51
12	OFS-01-03-01-02	Eviction of unwanted material	m³	6017.83	0.0048	66.39	29.003	399494.08
13	OFS-01-03-01-03	Soil Compactation	m³	769.78	0.0015	20.22	1.13	15563.67
14	**OFS-01-03-02**	**Structure**						
15	OFS-01-03-02-01	Retaining Walls						
16	OFS-01-03-02-01-001	Pouring concrete in Reataining walls f'c=280 kg/cm², includes pump transport	m³	317.11	0.0026	36.27	0.835	11500.82
17	OFS-01-03-02-01-002	Reinforcing steel cutting fy=4200 kg/cm²	tonnes	9.72	0.0011	8.64	0.011	84.02
18	OFS-01-03-02-01-003	Formwork Wood cutting of retaining walls	tonnes	2.38	0.0022	17.28	0.005	41.1
19	OFS-01-03-02-02	Foundation						
20	OFS-01-03-02-02-001	Pouring concrete in foundation beams f'c=280 kg/cm², includes pump transport	m³	441.36	0.0025	33.94	1.088	14981.44
21	OFS-01-03-02-02-002	Reinforcing steel cutting fy=4200 kg/cm²	tonne	31.11	0.0016	12.96	0.05	403.14
22	OFS-01-03-02-02-003	Formwork wood cutting of foundation beams	tonne	1.54	0.0027	21.6	0.004	33.36
23	OFS-01-03-02-03	Staircase and Ramps						
24	OFS-01-03-02-03-001	Pouring concrete in staircase and ramps f'c=280 kg/cm², includes pump transport	m³	62.86	0.0061	84.59	0.386	5317.65
25	OFS-01-03-02-03-002	Reinforcing steel cutting fy=4200 kg/cm²	tonnes	12.07	0.0011	8.64	0.013	104.28
26	OFS-01-03-02-03-003	Formwork wood cutting of staircase and ramps	tonnes	0.57	0.0022	17.28	0.001	9.93
27	OFS-01-03-02-04	Columns						

28	OFS-01-03-02-04-001	Column Pouring concrete f'c=280 kg/cm², includes pump transport	m³	214.22	0.0035	48.29	0.751	10344.58
29	OFS-01-03-02-04-002	Reinforcing steel cutting fy=4200 kg/cm²	tonnes	47.74	0.0016	12.96	0.077	618.75
30	OFS-01-03-02-04-003	Formwork wood cutting of columns	tonnes	2.28	0.0027	21.6	0.006	49.23
31	OFS-01-03-02-05				Beams			
32	OFS-01-03-02-05-001	Pouring concrete in beams f'c=280 kg/cm², includes pump transport	m³	319.97	0.0031	43.31	1.006	13856.79
33	OFS-01-03-02-05-002	Reinforcing steel cutting fy=4200 kg/cm²	tonnes	40.57	0.0016	12.96	0.066	525.82
34	OFS-01-03-02-05-003	Formwork wood cutting of beams	tonnes	2.67	0.0027	21.6	0.007	57.73
35	OFS-01-03-02-06				Slabs			
36	OFS-01-03-02-06-001	Pouring concrete in slabs f'c=280 kg/cm², includes pump transport	m³	387.82	0.003	41.54	1.17	16110.24
37	OFS-01-03-02-06-002	Reinforcing steel cutting fy=4200 kg/cm²	tonnes	33.44	0.0011	8.64	0.036	288.88
38	OFS-01-03-02-06-003	Formwork wood cutting of slabs	tonnes	5.38	0.0022	17.28	0.012	92.99
			Total:				**843.6**	**10338068.58**

3. Results

3.1. Overall Results

The evaluation of CO_2 emissions showed that the EFS system produced the highest emissions compared to the OFS and ODS systems. The emissions in the EFS system were approximately 39% higher (around 480 tonnes) than the emissions in the OFS and ODS systems (Figure 3). Between the OFS and ODS systems, the emissions of CO_2 in the ODS system were approximately 5% higher (around 43 tonnes) than in the OFS system (Figure 3). Energy consumption (Figure 3) showed a similar trend in comparison with the EFS, OFS, and ODS systems, with the highest consumption in the EFS system at around 58% (around 6 million MJ) higher than in the OFS and ODS systems. Similar to CO_2 emissions, the ODS system consumed slightly more energy (around 6%) than the OFS system.

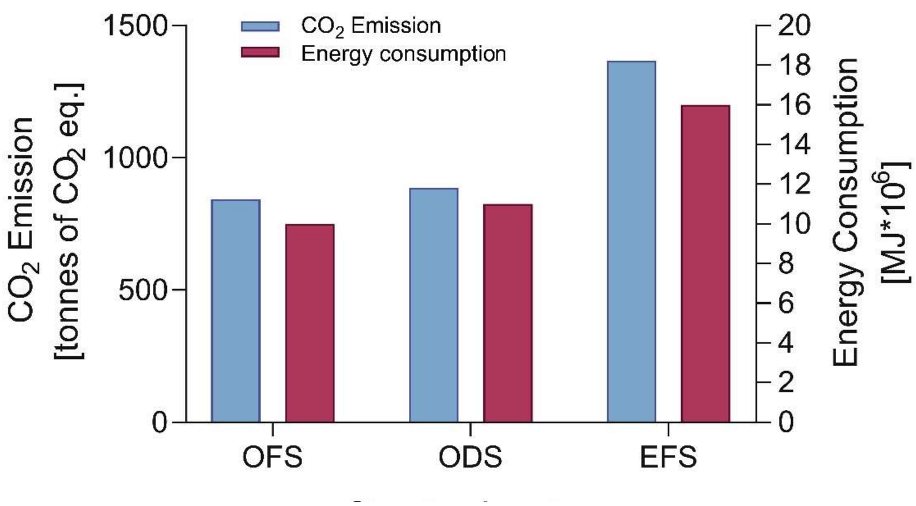

Figure 3. CO_2 emission and energy consumption per structural system.

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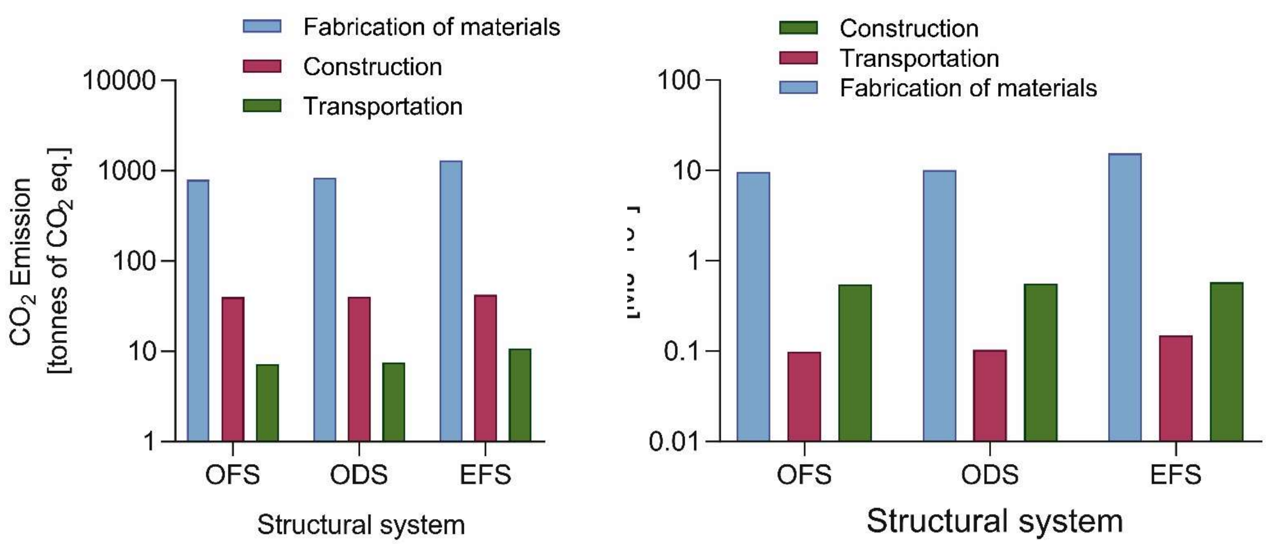
3.2. A detailed Description of Results Per Building Stage

The life cycle assessment showed that the EFS system had the highest CO_2 emissions and energy consumption compared with the OFS and ODS systems (Section 3.1). The assessment considered the stages of material fabrication, transportation, and building construction, with the fabrication stage accounting for the largest CO_2 emissions and energy consumption (Figure 4). The differences in CO_2 emissions and energy consumption between the OFS and ODS systems were insignificant across stages, except for the fabrication stage where the ODS system had 5% higher emissions and consumption than the OFS system (Figure 4). When comparing the OFS and ODS systems with the EFS system, the fabrication stage accounted for over 40% of the total CO_2 emissions and energy consumption.

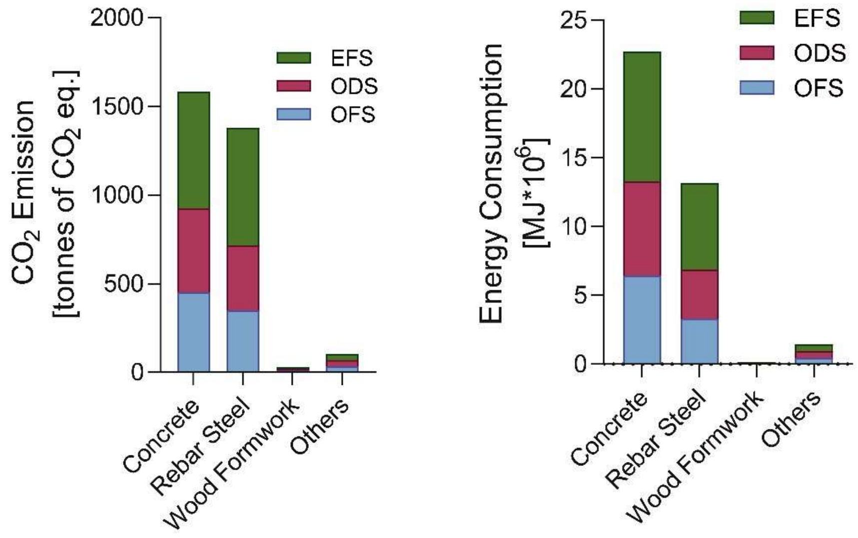


(a) (b)

Figure 4. (a) CO_2 emission per activity in each structural system and (b) Total energy consumption per activity in each structural system.

3.3 Influence of the Material on the Emission of CO_2 and Energy Consumption

The influence of materials on the emission of CO_2 and energy consumption considers the impact of ready-mixed concrete, steel rebar reinforcement, wooden formwork, and soil-related activities in the three structural systems (OFS, ODS, and EFS). Results showed that ready-mixed concrete and steel rebar reinforcement are the main contributors to CO_2 emissions and energy consumption, accounting for more than 50% and 40% of overall emissions, respectively (Figure 5). Wooden formwork and soil removal activities have a relatively small impact, contributing to less than 1% and 5% of emissions, respectively. Notably, in the EFS system, steel rebar reinforcement and ready-mixed concrete have similar CO_2 emissions, with steel rebar reinforcement emissions being slightly higher (around 0.5%) than ready-mixed concrete emissions (Figure 5). In contrast, in the OFS and ODS systems, ready-mixed concrete was the main source of CO_2 emissions, accounting for more than 27% more emissions than steel rebar reinforcement. Based on the overall contribution of materials to CO_2 emissions and energy consumption, the structural systems can be ranked from highest to lowest environmental impact as EFS, ODS, and OFS.

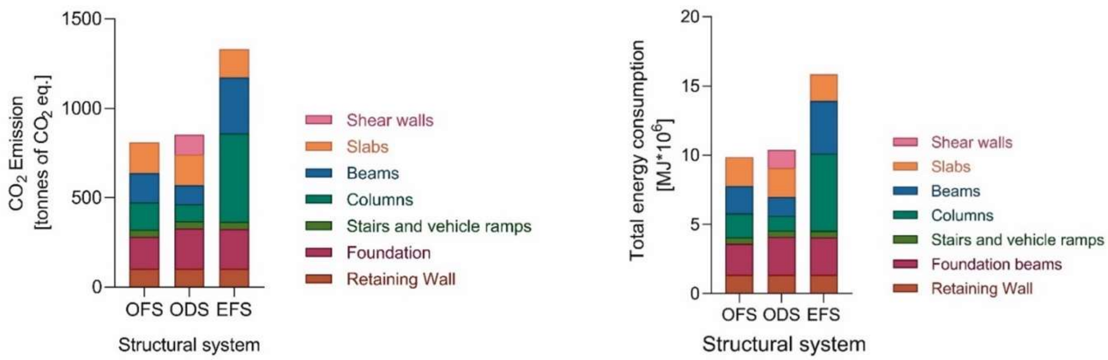


(a) (b)

Figure 5. (a) CO2 emission per material and (b) total energy consumption per material.

3.4 Environmental Impact of the Structural Elements Used in Each Structural System

The structural elements that contribute the most to CO_2 emissions and energy consumption in the OFS and ODS systems are the foundation, beams and slabs (Figure 6). In the OFS system, foundation beams account for around 22% of the total CO_2 emissions and 22.7% of the total energy consumption. In the ODS system, these figures increase to approximately 26.4% and 26.3%, respectively. In the EFS system, foundation beams contribute to around 16% of the total CO_2 emissions and 17% of the total energy consumption (Figures 6 and 7). Notably, in the EFS system, columns and beams, rather than foundation beams, are the main sources of CO_2 emissions and energy consumption, which are roughly two times higher than those produced by foundation beams. This difference in results is due to the modifications made to the columns and beams in the EFS system to reduce drift and achieve a similar structural response to the ODS system, allowing for a better assessment of the impact of materials and energy on the EFS system's environmental impact.



(a) (b)

Figure 6. (a) CO_2 emission per structural element and (b) Total energy consumption per structural element.

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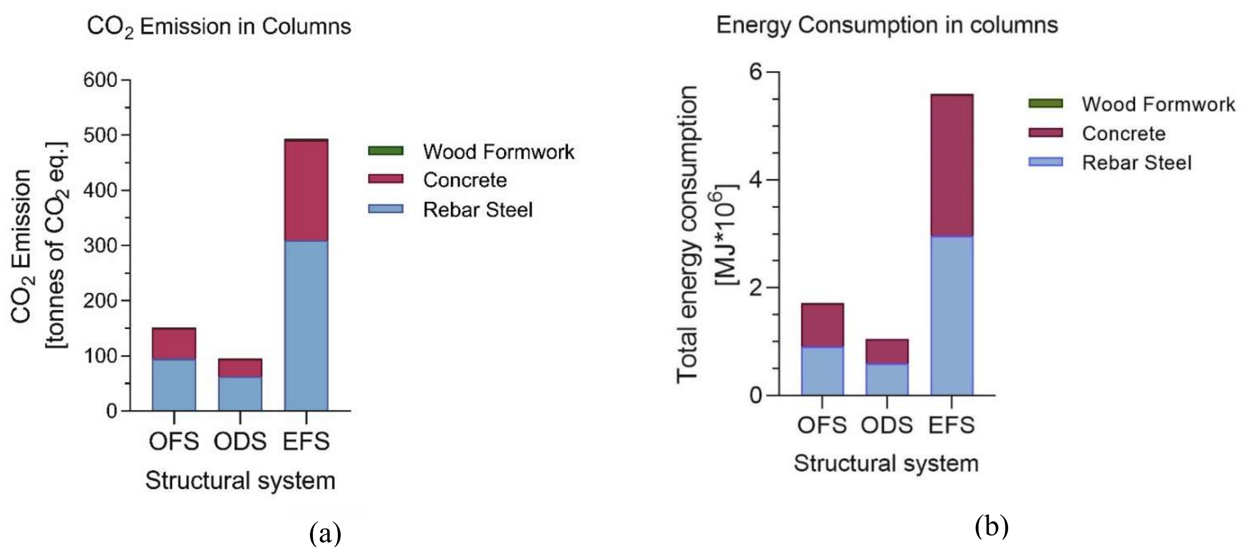

Figure 7. (a) CO_2 emission in structural system and material by columns and (b) Total energy consumption in structural system and material by columns.

Further analysis of the components of the structural elements in terms of the materials used showed that steel reinforcement in columns (maximum reinforcement ratio elements) accounts for approximately 64% and 54% of CO_2 emissions and energy consumption, respectively, in all three structural systems. In contrast, ready-mixed concrete is the main source of emissions in minimum reinforcement ratio elements, such as slabs, contributing to around 58% and 68% of CO_2 emissions and energy consumption, respectively (Figures 6 and 7). Therefore, steel is the primary source of emissions in maximum reinforcement ratio elements, while ready-mixed concrete is the main source in minimum reinforcement ratio elements.

4 Discussion

The design and construction of buildings is a complex process that requires consideration of various technical factors, including mechanical resistance, environmental impact, and sustainability [9,10,32,33]. While traditional building design in developing countries has focused primarily on structural design, it has largely neglected environmental factors such as emissions of CO_2 and energy consumption[34,35]. This led to buildings that are likely to be environmentally inefficient. The study discussed in this article is the first of its kind in Ecuador, comparing the carbon footprint of different structural systems (OFS and ODS) with an equivalent structure (EFS). The results of this study provide evidence of how structural decision made into the design of building structures, could incurred in higher or lower levels of pollution; focusing on the context of developing country with a high seismic risk.

There is a notable impact of the materials utilized on CO_2 emissions and energy consumption within the construction industry. The use of different materials such as concrete, steel, and wood can have different environmental impacts. For instance, concrete has a high carbon footprint due to the production of cement, which is one of the major contributors to CO_2 emissions. In contrast, wood has a lower carbon footprint due to its renewable nature and the ability to store carbon. In addition to the type of material, the origin of the material also plays a role in the emission of CO_2 and energy consumption. Materials that are sourced locally have a lower carbon footprint compared to materials that are transported from distant locations. This is because the transportation of materials consumes energy and emits CO_2, adding to the overall environmental impact of the building. Furthermore, the durability and maintenance requirements of the materials used can also impact the emission of CO_2 and energy consumption. Materials that require frequent maintenance and replacement can have a

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higher environmental impact compared to materials that are durable and require less maintenance. Research by Resch et al. (2020) [36] found that transportation of materials significantly contributes to CO_2 emissions in building construction, averaging around 6%. Overall, the choice of materials used in construction can have a significant impact on the emission of CO_2 and energy consumption. Sustainable and eco-friendly materials, sourced locally and with low maintenance requirements, can reduce the environmental impact of the building.

The life cycle assessment conducted for each structural system (Figure 3) indicated that the OFS system had the lowest CO_2 emissions and energy consumption among the three alternatives. However, the earthquake-resistant performance of the OFS system is unsatisfactory, as it shows a story drift of 1.75%, which may be deemed excessively high. This drift has recently been associated with non-structural damage, resulting in numerous deaths in recent earthquakes [20]. The ODS system demonstrated the best balance between environmental impact and structural behaviour. While CO_2 emissions and energy consumption were slightly higher than those of the OFS system by 5% and 6%, respectively, the ODS system's short drift (0.82%), which less than half the storey drift generated in the OFS, it substantially reduced the impact of earthquakes on the building's non-structural components, preventing deaths from these causes. Therefore, the ODS system is the most suitable alternative that offers both environmental efficiency and earthquake-resistant performance.

There is a direct relationship between the need to create more rigid structures to mitigate the effects of seismic forces and pollution levels. In this sense, the EFS is a clear example of an ill-advised way to generate a rigid structure, as it incurs in high levels of pollution. A similar finding was reported in a life cycle assessment of buildings in Atlanta, USA, where energy consumption and CO_2 emissions increased in more complex, heavier and rigid structures compared to lighter structures [9]. Therefore, it is necessary to seek a balanced approach to forming a rigid structure with low pollution levels, as achieved with the ODS. Regardless of the chosen structural system (EFS, OFS, and ODS), the maximum CO_2 emissions and energy consumption (about 90%) were recorded during the materials fabrication stage. This can be attributed to industrial processes involved in material fabrication, such as steel melting and heat treatment, or cement clinker production. Previous studies examining the environmental impact of steel and concrete used in residential [33] and commercial buildings in Singapore [37] reported similar findings. It is worth noting that the location of the building has a significant impact on the materials fabrication stage. For instance, countries in the Circum-Pacific belt, known for their high seismic activity, require more robust structural systems, which requires more concrete, and steel, leading to higher CO_2 emissions and energy consumption during fabrication compared to areas with lower seismic activity such as the East Coast of the United States.

The production of concrete and steel, which are the primary materials used in each structural component that provides mechanical resistance, contributes significantly to carbon emissions and energy consumption. In the OFS and ODS systems, the major contributor to CO_2 emissions and energy consumption was the ready-mixed concrete. However, in the EFS system, despite the abundance of ready-mixed concrete, most of the emissions and consumption were caused by steel. This outcome can be attributed to the fabrication process of steel, which involves several heating processes, including melting and heat treatments, resulting in significant pollutant emissions [38]. In contrast, fabrication of ready-mixed concrete requires only one heating process [39]. Moreover, the EFS system has large, robust structural elements that require substantial amounts of steel, altering the weight ratio between steel and ready-mixed concrete. The ratio is higher in the EFS than in the OFS and ODS systems, making steel reinforcement the primary contributor to CO_2 emissions.

Another notable difference between the optimised systems (OFS and ODS) and the EFS was the environmental impact of the structural elements. In the OFS and ODS systems, foundation beams and slabs accounted for the majority of emissions and energy consumption, while in the EFS, beams and columns were the main contributors of pollutants into the environment. This discrepancy could be explained by the balanced number of structural elements in the optimised systems, which resulted in no significant differences in emissions between them. However, in the EFS system, CO_2 emissions and energy consumption of beams and columns were at least ten times higher than those of other structural elements (eg. slabs). This highlights the fact that the EFS system requires more columns and beam elements (approximately 419% more columns and 190% more beams) to achieve a similar storey drift compared to the ODS system, which has a similar structural response with fewer columns and beams.

This study examined the structural behaviour of three different systems and their impact on the environment. In developing countries, there is limited information available on how the structural system of buildings affects the environment, with most studies focusing on architectural design or the type of material used [11,12,14]. By incorporating environmental considerations into the design of structures, we offer a new methodology for creating sustainable buildings that significantly reduce the carbon footprint compared to traditional design approaches. Furthermore, we also assessed the structural behaviour of these systems, with a focus on storey drift as the primary structural variable. The ODS system, which combines the benefits of lower CO_2 emissions and lower storey drift, underscores the significance of storey drift in the structural response of the system and its environmental impact. This system offers the advantage of combining the low CO_2 emissions and energy consumption of the OFS system with the mechanical strength of the EFS system.

As the field of environmental impact assessment for buildings in Ecuador is still in its infancy and our study is the first to integrate earthquake-resistant design and environmental impact analysis, there is limited information available on the factors that contribute to CO_2 emissions and energy consumption during the construction process. To overcome this limitation, we relied on published databases to quantify the environmental impact of structural elements and materials in each of the three structural systems [25–27]. Furthermore, a more comprehensive life cycle assessment that takes into account the role of building occupants will provide additional insights into the environmental impact of new constructions.

Table 14. compares the results obtained in the different stages of the life cycle, as can be seen in each of the different studies in scope, some cover more stages, others less. However, in most studies [8,9,40] the results (maximum and minimum) are within the same order of magnitude, except for Suzuki's study et al., 1995 [33] conducted in Japan.

Author	Location	Embodied carbon of concrete structures [tonnes of CO2 eq.]		
		Manufacture phase	Transportation phase	Construction phase
Moussavi & Akbarnezhad, 2015	USA	548-847	37-58	50-66
Suzuki et al., 1995	Japan	2232-3034	-	-
Cole, 1998	Canada	-	33	29
Kua & Wong, 2012	Singapore	871	-	-
This study	Ecuador	796-1313	7-11	40-43

5 Conclusion

This study compared three structural systems—EFS, OFS, and ODS—and evaluated their environmental impact in terms of CO_2 emissions and energy consumption. Results showed that concrete and reinforcing steel fabrication contributed to a greater proportion of carbon emissions and required substantial energy. Ready-mixed concrete was the primary contributor to the OFS and ODS systems, while steel dominated in the EFS system.

In terms of emissions and energy consumption distribution within each system, foundation beams and slabs were significant in the OFS and ODS systems, while beams and columns played a major role in the EFS system. This disparity can be attributed to the balanced number of structural elements in the optimized systems, where emissions and energy consumption of beams and columns in the EFS system exceeded the others by at least ten times.

The study also found that the ODS system that CO_2 emissions were related to a lower storey drift, highlighting the importance of storey drift in the structural response and environmental impact. It emphasized the need for a new methodology to design sustainable structures that consider the carbon footprint and reduce environmental impact.

Overall, the study emphasizes the importance of considering environmental impact in the design and construction of building structures to minimize negative effects. As the first study in Ecuador to quantify and consider environmental impact when designing new buildings, it highlights that approximately 90% of overall CO_2 emissions and energy consumption occur during materials fabrication. To reduce the environmental impact of construction materials, new guidelines for more efficient production should be implemented. The study suggests the ODS system as the best option in designing new buildings in Quito, Ecuador, considering mechanical performance during earthquakes and identified CO_2 emissions and energy consumption. The ODS system highlights the potential to achieve buildings with highly efficient structural performance and reduced environmental impacts.

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